Probabilistic Guidance of a Swarm Deployed from the Back Shell of the Mars Spacecraft

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Abstract. This paper presents a probabilistic guidance algorithm for a swarm of assets deployed from the back shell of the Mars spacecraft. Such a swarm could provide valuable science data, with large spatiotemporal variation, from the Martian surface. Our probabilistic swarm guidance algorithm maximizes the coverage area of the swarm while uniformly distributing the assets on the Martian surface and guaranteeing strong-connectivity of the swarm's communication network topology. Numerical simulations demonstrate the effectiveness and versatility of our probabilistic swarm guidance algorithm.

Keywords: swarm robotics, probabilistic swarm guidance

1 Introduction

The National Aeronautics and Space Administration (NASA) is considering multiple missions to Mars for a potential Mars Sample Return (MSR) campaign [1]. At the same time, a number of mission concepts (e.g., Prandtl-M glider [2], Tensegrity lander [3]) are being developed to fit in the empty space in the backshell of Mars spacecraft as secondary payloads. These assets could be deployed as secondary payloads after the primary payload has separated from the backshell of Mars spacecraft. We envisage that a swarm of such secondary payloads (100–1000 assets) could be deployed from the backshell of Mars spacecraft for distributed science on Mars (see Fig. 1). In this paper we present a guidance algorithm for such a swarm.

From the science perspective, the key requirement on the swarm distribution would be to maximize its coverage area while staying away from some regions. In addition, the swarm has to maintain a strongly connected communication network topology so that the science data collected by each agent can be sent to Earth via the backshell of Mars spacecraft. These requirements and constraints are captured by a desired swarm distribution on the Martian surface. The objective of our probabilistic swarm algorithm is to determine the release time, angle of deployment, and initial velocity of each asset so that the swarm

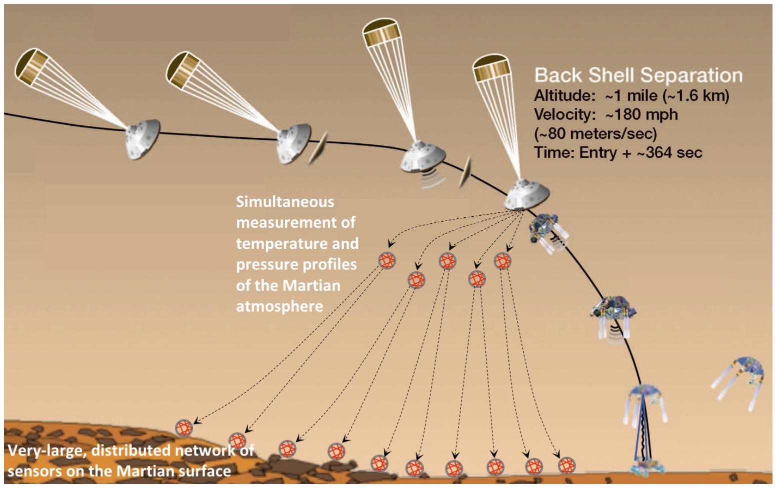


Fig. 1. Deployment of a swarm of assets from the backshell of Mars spacecraft

achieves the desired distribution on the Martian surface, despite the assets being subject to significant environmental disturbances. Moreover, the assets do not have position or attitude sensors and would fall towards the Martian surface in an open-loop manner after being deployed from the Mars spacecraft. This lack of feedback control makes this swarm guidance problem fundamentally different from existing probabilistic swarm guidance algorithms in the literature. For example, probabilistic swarm guidance using homogeneous or inhomogeneous Markov chains [4–6] or optimal transport [7] requires position information of the assets. Our probabilistic swarm guidance algorithm captures the transition probabilities from different release times, angles of deployment, and initial velocities to locations on the Martian surface, and then maximizes the probability of the swarm achieving the desired distribution. This novel probabilistic swarm guidance algorithm is the main contribution of this paper.

This paper is organized as follows. The conceptual science objectives of the Martian swarm are discussed in Section 2. Section 3 presents the possible hardware assets that could be used for this swarm. Our probabilistic swarm guidance algorithm and numerical simulations are presented in Section 4. More numerical simulations are presented in Section 5 and the paper is concluded in Section 6. Here $\mathbb{N}$ and $\mathbb{R}$ represent the sets of natural numbers and real numbers respectively.

2 Possible Science Objectives of the Martian Swarm

A number of interesting science observations, with large spatiotemporal variation, could be carried out by a swarm of 1000 assets on the Martian surface. Here we present some possible science objectives of such a swarm:

– Measurement of temperature and pressure profiles
– Measurement of wind speed and understanding wind cycle
– Distributed Methane measurement
– Understanding water/humidity cycle between soil and atmosphere
– Understanding the interior properties using miniature seismographs
– Understanding soil properties using miniature spectrometer
– Gradiometry
– Understanding dynamics of polar ice caps
– Deploying sensor knowledge network for future missions

The key requirements on the swarm distribution from the science perspective are:

– The coverage area of the swarm should be maximized in order to maximize the spatiotemporal range of the data collected by the swarm.
– The communication network topology of the swarm should be strongly connected so that the science data collected by each agent can be sent to Earth via the backshell of Mars spacecraft.
– The swarm must stay away from the primary payload (the Martian rover) and other sensitive areas on the Martian surface for planetary protection purposes.

These requirements and constraints are captured while designing the desired swarm distribution on the Martian surface.

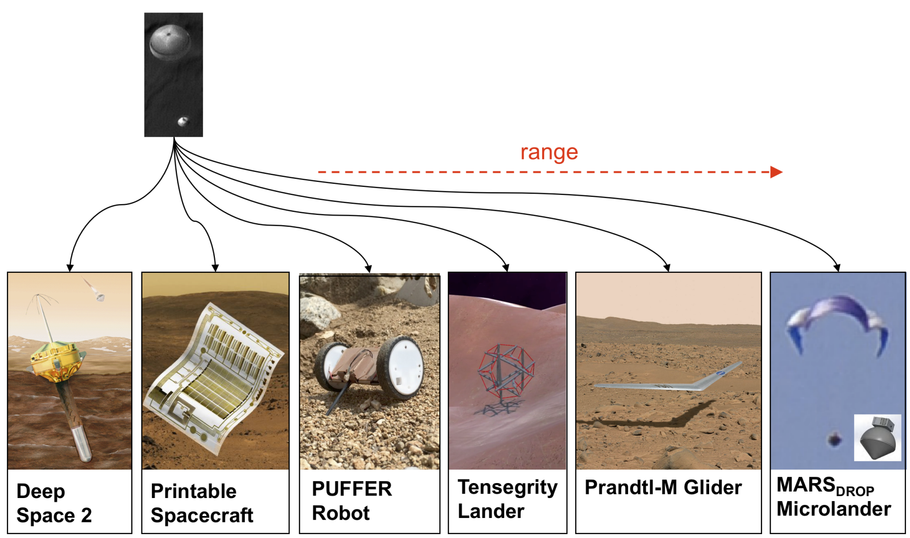


Fig. 2. Possible swarm assets, with increasing range after deployment

3 Possible Hardware Assets for the Martian Swarm

A number of concepts are being developed to fit in the empty space in the backshell of Mars spacecraft as possible secondary payloads, as shown in Fig. 2. These potential hardware concepts include:

- Deep Space 2 microprobe [8]
- Printable spacecraft [9]
- Pop-Up Flat Folding Explorer Robot (PUFFER) robot [10]
- Tensegrity lander [3]
- Prandtl-M glider [2]
- MARSdrop microlander [11]

In order to simplify the dynamics of these swarm assets, we use the ballistic trajectory dynamics in this paper. Let $\boldsymbol{x}_i(t) = \{x_i(t), y_i(t), z_i(t)\}$ represent the position of the i^{th} asset in an inertial coordinate frame fixed on the Martian surface. For given initial conditions in position $\boldsymbol{x}_i(0)$ and velocity $\dot{\boldsymbol{x}}_i(0)$, the dynamics of the assets is given by:

$$\ddot{\boldsymbol{x}}_i(t) = \{0, 0, -g_{\mathrm{M}}\}\,, \tag{1}$$

where $g_{\mathrm{M}} = 3.7\,\mathrm{ms}^{-2}$ represents the gravitational acceleration on Mars. We assume that the maximum initial velocities that can be imparted to an asset at the time of deployment by the deployment mechanism in the Mars spacecraft is $\pm 40\,\mathrm{ms}^{-1}$ in X and Y axes. We also assume the the assets experience a velocity disturbance at the time of deployment, which is bounded by $\pm 5\,\mathrm{ms}^{-1}$ in all three axes.

4 Probabilistic Swarm Guidance Algorithm

We assume that $N \in \mathbb{N}$ assets will be deployed as secondary payloads. In this section, we first generate the desired distribution of the swarm and then present the probabilistic swarm guidance algorithm to achieve it.

4.1 Required Area Density for Strong Connectivity

Let r_{comm} represent the maximum communication radius of each asset, i.e., each asset can communicate with any other asset that less than r_{comm} distance away from it. In this paper, we assume that $r_{\mathrm{comm}} = 60$ m [12].

The theoretical bound on the area density of a unfirmly distributed swarm that grantees that the communication network topology is strongly connected is given by [13]:

$$\lim_{N\to\infty} \mathbb{P}(\pi N r_{\mathrm{comm}}^2 - \log N \leq c) = e^{-e^{-c}}\,, \tag{2}$$

where $c \in \mathbb{R}$. Since this bound is not tight for finite number of agents, comparison of Monte Carlo simulation results and theoretical bounds for different number of assets N is shown in Fig. 3. These results show that the swarm distribution must have an area density of $\sqrt{N} r_{\mathrm{comm}} \geq 2$ in order to guarantee strong connectivity of its communication network topology.

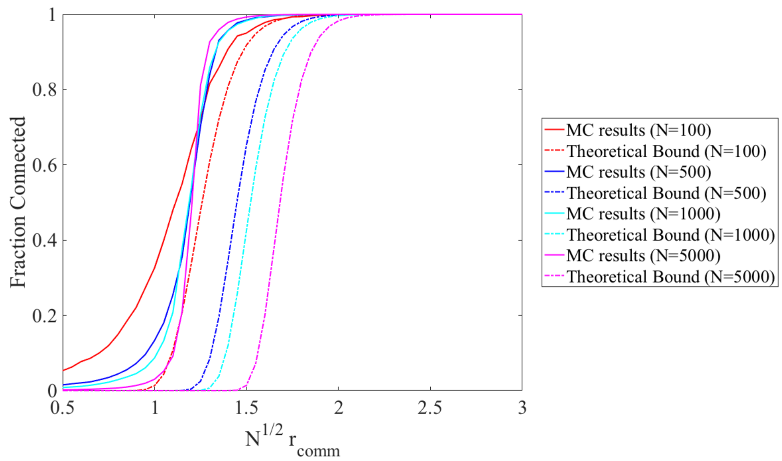


Fig. 3. Monte Carlo simulation results and theoretical bounds show the fraction of the swarm that is strongly connected, for different number of assets N

4.2 Design Desired Distribution for the Swarm

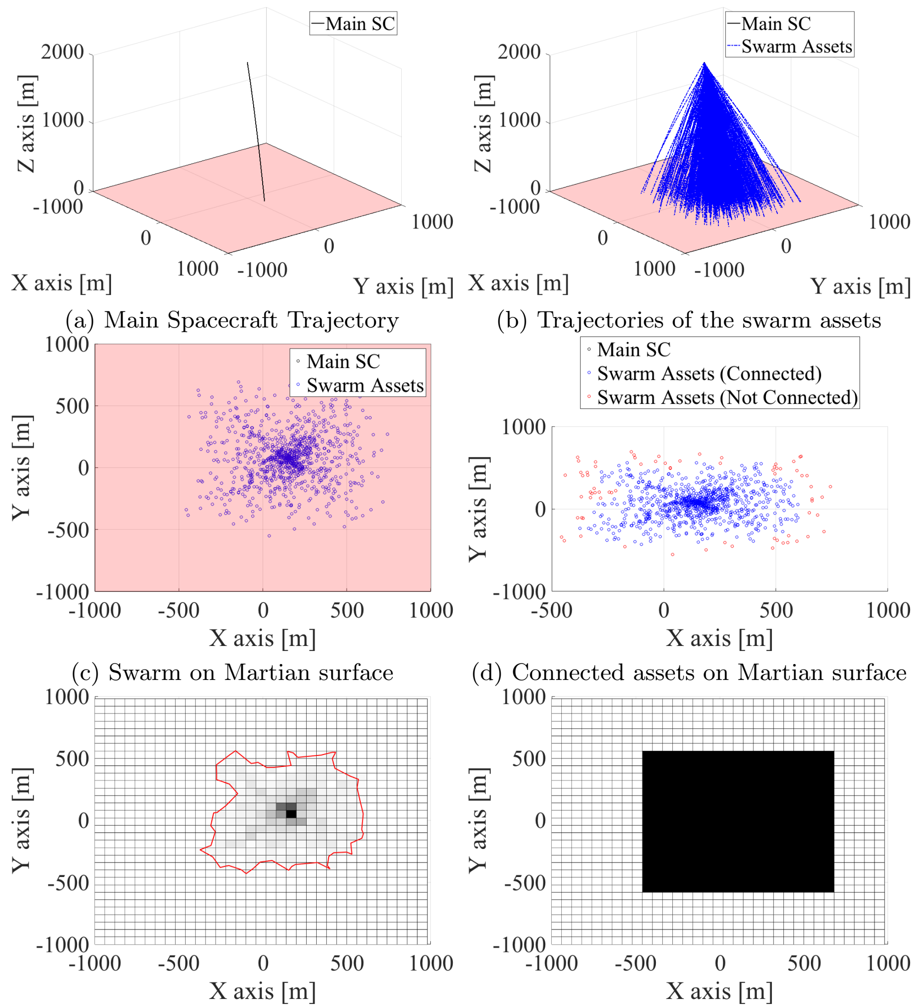
During the Entry Descent Landing (EDL) sequence, the Mars rover separates from the backshell of Mars spacecraft at $1.6-2$ km above the Martian surface and the Mars spacecraft is falling downwards at a speed of approximately $100\,\mathrm{ms}^{-1}$ [14]. A nominal trajectory of the backshell of Mars spacecraft, after separation, is shown in Fig. 4(a).

Assume that a swarm of 1000 assets are randomly released, with uniform randomness in release times and initial conditions. The trajectories of the swarm assets are shown in Fig. 4(b). Note that the assets are clustered around the central region where the main spacecraft landed, as shown in Fig. 4(c)–(e). Moreover, such a swarm non-uniformly samples the coverage area of approximately $2.3 \times 10^5\,\mathrm{m}^2$ and a number of peripheral assets are not connected to the dominant communication network. The red line in Fig. 4(e) shows the boundary of the strongly connected sub-group of the swarm. Clearly, a well-designed swarm guidance algorithm should be able to achieve a larger coverage area with better distribution of assets. This problem is the main focus of this paper.

The desired distribution of the swarm ($\boldsymbol{\mu}_d$) on the Martian surface that satisfies the area density requirement of $\sqrt{N} r_{\mathrm{comm}} \geq 2$ is given by Fig. 4(f). It covers an area of approximately $1.3 \times 10^6\,\mathrm{m}^2$ on the Martian surface.

4.3 Probabilistic Swarm Guidance Algorithm to achieve the Desired Distribution

Motivated by the probabilistic swarm guidance algorithm using inhomogeneous Markov chains [5], we design a Markov matrix to capture the transition probabilities from different release times, angles of deployment, and initial velocities



(a) Main Spacecraft Trajectory (b) Trajectories of the swarm assets

(c) Swarm on Martian surface (d) Connected assets on Martian surface

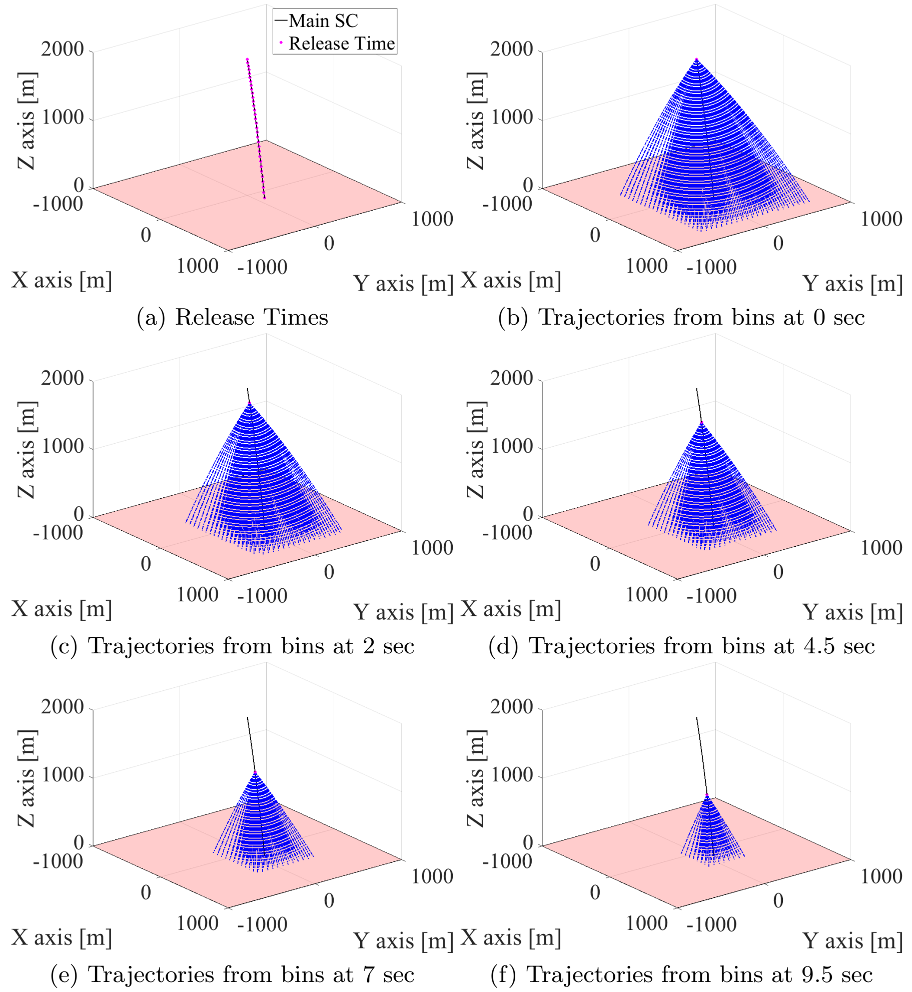
(e) Swarm distribution on Martian surface (f) Desired swarm distribution ($\boldsymbol{\mu}_d$)

Fig. 4. Swarm assets randomly released after backshell separation

to locations on the Martian surface, and then maximize the probability of the swarm achieving the desired distribution. Our probabilistic swarm guidance algorithm consists of three steps:

- Step 1: Designing bins with appropriate initial conditions.
- Step 2: Computing transition probabilities for each bin.
- Step 3: Maximizing probability of achieving the desired distribution.

Step 1: Designing Bins: The workspace on the Martian (i.e., approximately ± 1000 m on both axes from the main spacecraft landing site) is partitioned into



(a) Release Times (b) Trajectories from bins at 0 sec

(c) Trajectories from bins at 2 sec (d) Trajectories from bins at 4.5 sec

(e) Trajectories from bins at 7 sec (f) Trajectories from bins at 9.5 sec

Fig. 5. Trajectories from valid bins for a few release times

cells as shown in Fig. 4(e)–(f). Each cell is of the size $r_{\text{comm}} \times r_{\text{comm}}$ and there are a total of $n_{\text{cell}} = 1089$ cells on the Martian surface. Let $C[j]$ represent the j^{th} cell, for all $j \in \{1, \ldots, n_{\text{cell}}\}$.

The trajectory of the main spacecraft is discretized into time steps of 0.5 sec as shown in Fig. 5(a). There are a total of $n_{\text{time}} = 32$ discrete release time. Let $T[k]$ represent the k^{th} release time, for all $k \in \{1, \ldots, n_{\text{time}}\}$.

Let us define $n_{\text{cell}} \times n_{\text{bin}}$ bins, where the bin $B[k, j]$ encodes the initial velocities for an asset, released at time $T[k]$, to reach the center of the cell $C[j]$ in the absence of disturbances. During this step, the initial conditions for all bins $B[k, j]$, where $k \in \{1, \ldots, n_{\text{time}}\}$ and $j \in \{1, \ldots, n_{\text{cell}}\}$, are computed. If the initial conditions in a bin exceed the maximum initial velocity threshold, then those bins are considered invalid. The trajectories from valid bins for a few release times are shown in Fig. 5(b)–(f).

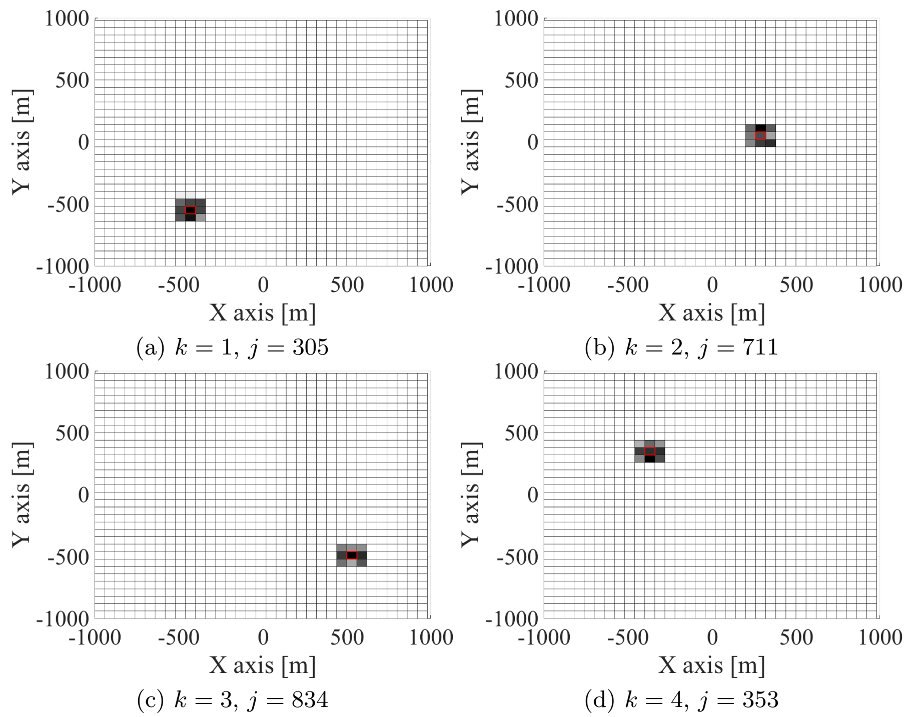
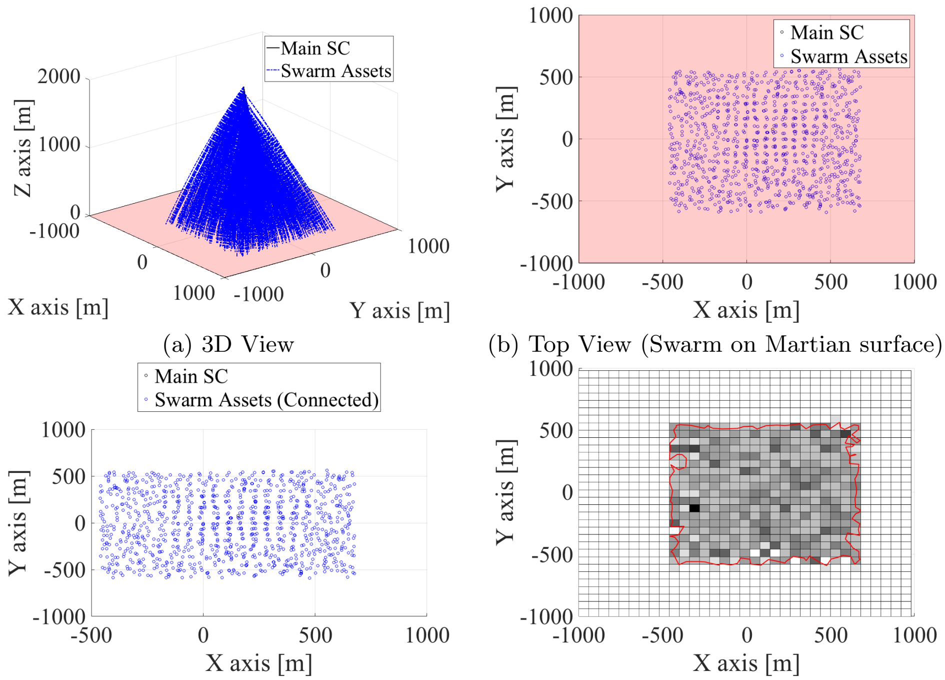


Fig. 6. Visualization of the Markov row $\boldsymbol{M}[(k-1) \times n_{\text{cell}} + j, :]$ for a few bins, where the red boundary denotes cell $C[j]$

Step 2: Computing Transition Probabilities: Let the Markov matrix $\boldsymbol{M} \in \mathbb{R}^{(n_{\text{time}} \times n_{\text{cell}}) \times (n_{\text{cell}})}$ capture the transition probabilities from bins (encoding release times and initial conditions) to cells on the Martian surface in the presence of disturbances. For example, the element $\boldsymbol{M}[(k-1) \times n_{\text{cell}} + j, \ell]$ in the Markov matrix encodes the probability that an asset released from bin $B[k, j]$ (i.e., at time $T[k]$ with initial conditions to reach cell $C[j]$) actually reaches cell $C[\ell]$ in the presence of disturbances, i.e.,

$$\boldsymbol{M}[(k-1) \times n_{\text{cell}} + j, \ell] = \mathbb{P}\left(C[\ell] | B[k, j]\right) . \tag{3}$$

During this step, all the elements in the Markov matrix $\boldsymbol{M}$ for valid bins are computed using Monte Carlo simulations. Thus the bins encode deterministic initial conditions for the assets, but the probabilistic final location of the assets on the Martian surface is captured by the Markov matrix. The Markov rows for a few valid bins are shown in Fig. 6.



(a) 3D View (b) Top View (Swarm on Martian surface)

(c) Connected Assets on Martian Surface (d) Probability Distribution on Martian Surface

Fig. 7. Swarm assets, deployed using our probabilistic swarm guidance algorithm, achieve the desired distribution

Step 3: Maximizing Probability of Achieving the Desired Distribution: Let the variable $\boldsymbol{A} \in \mathbb{Z}_{\geq}^{1\times(n_{\text{time}}\times n_{\text{cell}})}$ represent the assignment of the N assets to the $n_{\text{time}} \times n_{\text{cell}}$ bins, where $\mathbb{Z}_{\geq}$ represents the set of non-negative integers and $\boldsymbol{A}\mathbf{1}^{(n_{\text{time}}\times n_{\text{cell}})\times 1} = N$. The probabilistic swarm distribution, if agents are released as per the assignment $\boldsymbol{A}$ is given by $\boldsymbol{\mu}_s = \boldsymbol{AM}$. The desired swarm distribution $\boldsymbol{\mu}_d \in \mathbb{R}^{1\times n_{\text{cell}}}$ is given in Fig. 4(f). Our objective is to minimize the difference between $\boldsymbol{\mu}_s$ and $\boldsymbol{\mu}_d$ using the following optimization problem:

$$\min_{\boldsymbol{A}\in\mathbb{Z}_{\geq}^{1\times(n_{\text{time}}\times n_{\text{cell}})}} D_{L_1}(\boldsymbol{\mu}_s, \boldsymbol{\mu}_d) \tag{4}$$

$$\text{subject to } \boldsymbol{\mu}_s = \boldsymbol{AM}\,, \tag{5}$$

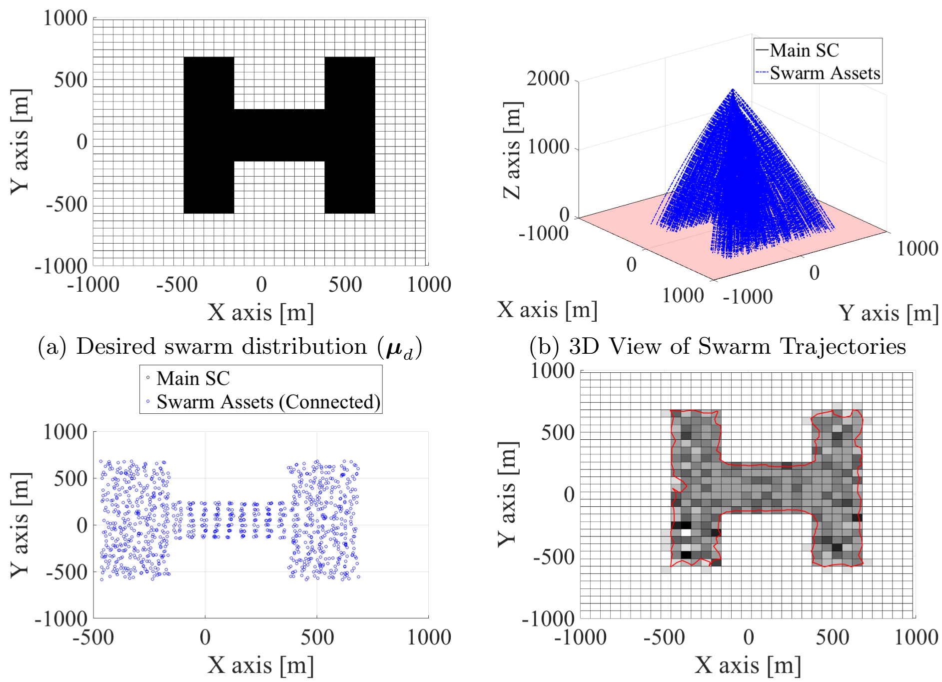
$$\boldsymbol{A}\mathbf{1}^{(n_{\text{time}}\times n_{\text{cell}})\times 1} = N\,. \tag{6}$$

Here D_{L_1} represents the L_1 distance between the two distributions. This optimization problem is solved during this step.

The trajectories of the swarm assets deployed using our probabilistic swarm guidance algorithm are shown in Fig. 7. Note that the assets are uniformly distributed over a large region of approximately $1.3 \times 10^6\,\text{m}^2$ on the Martian surface, which is ≈ 5 times larger than the coverage area obtained from random deployment in Fig. 4. Moreover, the swarm's communication network topology is strongly connected. Thus, our probabilistic swarm guidance algorithm achieves the desired distribution of assets on the Martian surface.

5 Numerical Simulations

Here we show that any desired distribution can be achieved using our probabilistic swarm guidance algorithm, if the desired location on the Martian surface can be reached by the swarm assets. Fig. 8 and Fig. 9 show that the swarm can easily incorporate complex shapes and no-go zones.



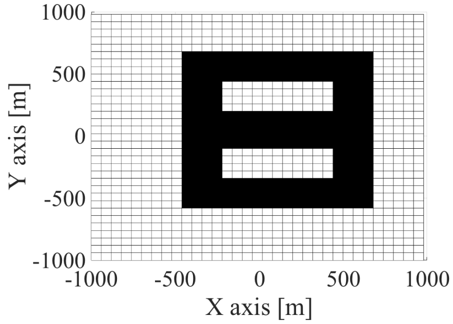
(a) Desired swarm distribution ($\boldsymbol{\mu}_d$) (b) 3D View of Swarm Trajectories

(c) Connected Assets on Martian Surface (d) Probability Distribution on Martian Surface

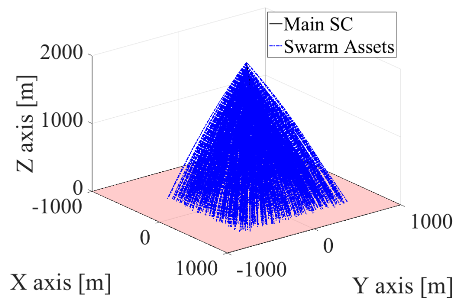
Fig. 8. Swarm assets achieve the new desired distribution

6 Conclusion

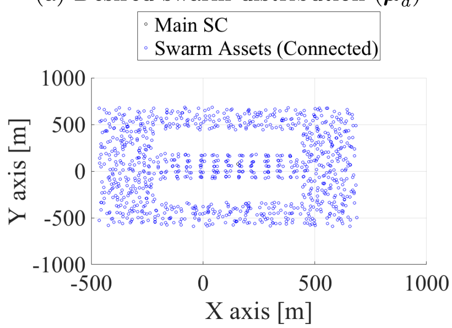
In this paper, we presented a probabilistic swarm guidance algorithm for potential assets deployed from the back shell of the Mars spacecraft. Our probabilistic swarm guidance algorithm maximizes the coverage area of the swarm while uniformly distributing the assets on the Martian surface and guaranteeing strong-connectivity of the communication network topology. Numerical simulations with



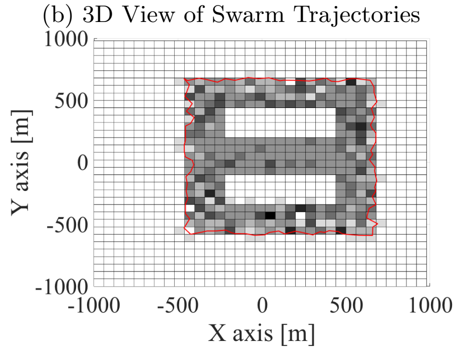
(a) Desired swarm distribution ($\boldsymbol{\mu}_d$)



(b) 3D View of Swarm Trajectories



(c) Connected Assets on Martian Surface



(d) Probability Distribution on Martian Surface

Fig. 9. Swarm assets achieve another new desired distribution, with no-go zones

1000 assets and 60 m communication radius show that the swarm could cover a large region of approximately $1.3 \times 10^6\ \mathrm{m}^2$ on the Martian surface. Numerical simulations also show that the probabilistic swarm guidance algorithms can be used to achieve complex shapes with no-go zones. Such a swarm on the Martian surface could yield valuable science data over a large spatiotemporal range.

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